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Spectral Radiance and Emissivity of Plasma

and Temperature Determination

10 JANUARY 1962

Prepared by ALLEN E. FUHS

Prepared for DEPUTY COMMANDER AEROSPACE SYSTEMS

AIR FORCE SYSTEMS COMMAND

UNITED STATES AIR FORCE

Inglewood, California

PHYSICAL RESEARCH LABORATORY

AEROSPACE CORPORATION

SPECTRAL RADIANCE AND EMISSIVITY OF PLASMA

AND TEMPERATURE DETERMINATION

by

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FIGURES

ABSTRACT

A method used to determine the temperature of a flame is to measure its spectral radiance and spectral emissivity. The ratio of these two measured quantities provides a point on the blackbody curve, if the flame is effectively in equilibrium. Sufficient measurements are taken throughout a wavelength region to trace out an experimentally determined blackbody curve. This curve is compared with a series of curves that have been plotted by using different temperatures in Planck's radiation law. The temperature used to obtain the plotted curve that best coincides with the experimentally determined blackbody curve is designated as the flame temperature.

This method is reviewed with the viewpoint of applying it to the measurement of plasma temperature. The technique appears to be feasible for continuous plasma sources with temperatures up to about $15,000^{\circ}$K. Experimental complexity makes it less attractive above that temperature. The method provides a temperature determination procedure utilizing many different radiative processes. Hence, the temperature determined by this method reflects more clearly the energy content and energy distribution.

I. INTRODUCTION

One method used to determine the temperature of a flame is to measure the spectral radiance and the spectral emissivity (Ref. 1). The ratio of these two quantities provides a point on the blackbody curve, if the flame is effectively in equilibrium. Repeated measurements give points which trace out the blackbody emissive power curve. The experimentally determined curve is compared with a series of curves that have been plotted using different temperatures in Planck's radiation law. The temperature used to obtain the calculated curve that best coincides with the experimental data is termed the flame temperature. To facilitate comparison of the two curves a log-log plot is used; the blackbody energy distribution curve has the same shape for all temperatures on a log-log plot (Ref. 2). It is of interest to examine this method to determine its applicability to measurement of plasma temperatures.

II. RELATIONSHIP OF SPECTROMETER MEASUREMENTS TO SPECTRAL RADIANCE AND EMISSIVITY

The deflection of the spectrometer recorder when viewing the plasma will be given by

$$R_p = C \int_0^\infty N_{\lambda p} \epsilon_\lambda \Phi(\lambda) d\lambda \, , \tag{1}$$

where C is a calibration constant independent of wavelength, $N_{\lambda p}$ is the blackbody radiance function (Planck's radiation law) at the temperature of the plasma, ϵ_λ is spectral emissivity and $\Phi(\lambda)$ is the slit function. Ideally $\Phi(\lambda)$ could be replaced by a delta function, but practically it is a function

sharply peaked at the wavelength setting of the instrument. Over the wavelength interval where $\phi(\lambda)$ gives significant contributions, $N_{\lambda p}$ is nearly constant and can be removed from the integration. Hence,

$$R_p = CN_{\lambda p} \int_0^\infty \epsilon_\lambda \phi \, d\lambda = CN_{\lambda p} \bar{\epsilon}_\lambda \, , \tag{2}$$

where the bar over the spectral emissivity means an effective value.

The spectral emissivity is determined by two measurements. In the first measurement the radiance of a radiation source is determined. The recorder deflection when viewing the source is given by

$$R_s = C \int_0^\lambda N_{\lambda s} \epsilon_{\lambda s} \phi(\lambda) \, d\lambda = CN_{\lambda s} \bar{\epsilon}_{\lambda s} \, , \tag{3}$$

where $N_{\lambda s}$ is the blackbody radiance calculated at source temperature and $\bar{\epsilon}_{\lambda s}$ is the effective source emissivity.

In the second measurement a chopper is used to view alternatively the source plus plasma and the plasma only as shown in Figure 1. When the hole in the chopper is aligned with the source, plasma and slit, the recorder deflection is

$$R_{sp} = C \int_0^\infty [N_{\lambda s} \epsilon_{\lambda s} (1-\epsilon_\lambda) + N_{\lambda p} \epsilon_\lambda] \phi(\lambda) \, d\lambda \tag{4}$$

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When only the plasma is observed the deflection is R_p. From the alternating signal it is possible to determine the peak-to-peak amplitude which is

$$R_A = R_{sp} - R_p = CN_{\lambda s} \overline{\epsilon_{\lambda s}(1 - \epsilon_\lambda)} \ . \tag{5}$$

If the source has a spectral emissivity which varies slowly over a wavelength interval equal to the width of the slit function, then

$$\overline{\epsilon_{\lambda s}(1 - \epsilon_\lambda)} \cong \overline{\epsilon}_{\lambda s}(1 - \overline{\epsilon}_\lambda) \ . \tag{6}$$

Combining equations 3, 5 and 6 gives

$$R_A = R_s(1 - \overline{\epsilon}_\lambda) \ , \tag{7}$$

or

$$\overline{\epsilon}_\lambda = (R_s - R_A)/R_s \ . \tag{8}$$

Once the effective spectral emissivity has been determined, equation 2 can be used to obtain a value for $N_{\lambda p}$.

III.   TYPICAL FLAME TEMPERATURE MEASUREMENTS

The results of experiments reported in Reference 1 are described here. By changing the word plasma to flame and the subscript p to f the analysis of the preceding section is applicable. A term for background radiation essential for experiments with flames but nonessential for plasma, has been omitted.

Figure 2 is a reproduction of Figure 3 of Reference 1. The molecules responsible for most of the radiation have been indicated along the curve. Observe that there is good fit of the blackbody curve to the data. Sufficient collisions have occurred to distribute the chemical bond energy released by the combustion in a manner characteristic of equilibrium at the flame temperature. Many different vibrational and rotational excited states are involved. In order for the data points to fit the blackbody radiance curve it is necessary to have the excited states populated according to equilibrium conditions.

Consider a hypothetical situation with the excited states giving the water vapor radiation at 10μ overpopulated. The results in Figure 2 would appear the same except that the data points near 10μ would be above the blackbody curve. Isolated departures from equilibrium are readily apparent using these methods. If the same hypothetical overpopulated H_2O excited states were used to determine a vibrational temperature, a misleading temperature would be obtained.

IV. REQUIREMENTS FOR EXTENDING THE METHOD TO LABORATORY PLASMAS

A. Wavelength Interval

The wavelength range investigated should include the peak of the blackbody curve. For a 2000°K flame the peak occurs between 1 and 2 micron. For a 8000°K plasma from an electric arc, the peak is in the visible region. Arc plasmas can be examined in an experimentally more favorable region. However, for temperatures above about 15000°K the difficulties of conducting experiments in the ultraviolet region are encountered.

B.   Source Requirements

The discussion leading to equation 6 has placed a slow-variation-with-wavelength restriction on the source spectral emissivity. If $\bar{\epsilon}_{\lambda s}$ is known and if $\Phi(\lambda)$ is known, the restriction is removed.

A requirement that the source radiative temperature exceed the plasma temperature might be expected. In principle, the source temperature need not be greater. However, from experimental limitations it is necessary to have R_A/R_p sufficiently large to avoid signal-to-noise problems. In order to neglect background radiation, the source must be many times brighter.

If R_A were larger than R_s, equation 7 would yield negative values for $\bar{\epsilon}_\lambda$. This cannot occur since R_s is always longer than R_A, regardless of source temperature relative to plasma temperature. Assuming that plasma temperature exceeds 15000°K and that one is willing to pay the price of working in the UV, then the selection of source becomes difficult, if not impossible. A tuneable maser (see, for example, Reference 3) may be the solution.

C.   Chopper Speed

For transient events, the reciprocal of the chopping frequency must be much less than the time of the event. For arc plasmas this should not pose any difficulties. However, for plasmas obtained by shock waves or by a magnetic pinch, the chopper frequency would be very large (many megacycles) causing problems. A Kerr cell might be employed as a chopper.

V. SPECTROGRAM OF AN ARC PLASMA

Figure 3 is a spectrogram which shows spectra from a plasma arc jet operating with argon. Run 1 is a calibration spectra using a mercury lamp. The other runs are for various operating conditions and spectrograph settings. Molecular spectra are present as evidenced by the CN Violet bands. A few lines associated with atomic transitions of neutral (LiI) and ionized species (A II) are identified. Also note the continuum radiation. The portion of the spectrum shown in Figure 3 may include or be slightly on the red side of the peak of blackbody radiance curve at the plasma temperature.

There is sufficient variety of radiative processes occurring in a plasma arc jet so as to make the method attractive. The radiance is not dependent solely on a few atomic lines.

VI. CONCLUSIONS

It seems feasible to extrapolate the technique to continuous plasma with temperature up to about $15000^{\circ}K$. Above that temperature, plasmas are usually of a transient nature imposing severe requirements on the chopper and spectrometer. Also at higher temperatures a suitable radiation source may not be available. A maser, which can be tuned, would appear to be the answer to the source problem.

The method provides a temperature determined from many different radiative processes, i.e., atomic transitions, radiative recombination, molecular electronic transitions, and bremsstrahlung. This experimental technique appears to have advantages, when compared to spectroscopic methods focusing on a particular radiative process, such as atomic transitions. The method readily finds and determines the extent of isolated departures from equilibrium provided such an equilibrium exists.
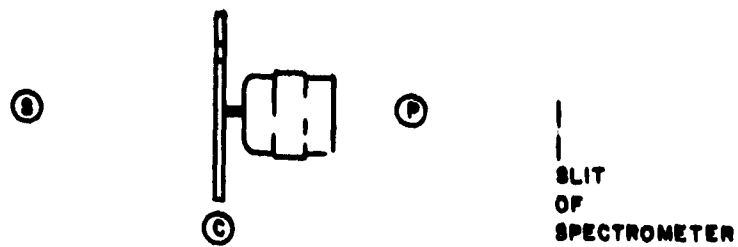
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Figure 1. A schematic diagram of the apparatus required to determine the spectral emissivity
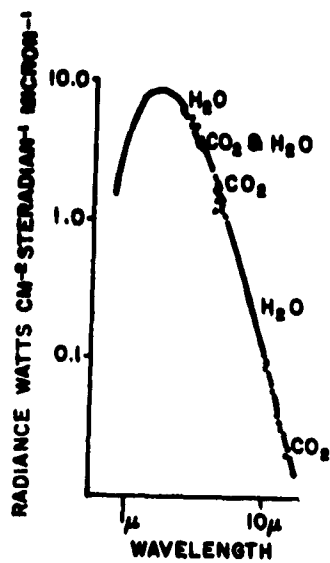

Figure 2. Reproduction of figure 3 of reference 1

Figure 3. The spectrogram shows molecular bands, atomic transitions and a continuum due primarily to recombination radiation.

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